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Midlatitude Synoptic Scale Systems: Their Kinetic Energy Budgets and Role in the General Circulation

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ABSTRACT—The kinetic energy budgets of several examples of synoptic scale systems are reviewed. Included are systems containing a major cyclone development, the immediate cyclone vicinity, and the anticyclone preceding the cyclone development. These are then considered in terms of their role in the general circulation of the middle latitudes.

Results show that the cyclone system and cyclone vicinity are respectively about two and five times more active energetically than the general circulation. Further, when averaged with results of Petterssen and Smebye, the resulting mean cyclone system accounts for about one-third of the energetic activity of the middle latitudes. On the other hand, circulations associated with the anticyclone case exhibit much less intense energetic properties.

1. INTRODUCTION

Atmospheric processes in the middle latitudes have been the subject of extensive study by meteorologists for the past several decades. During the last 10–15 yr of this period, it has become increasingly apparent that much about the motion fields in these systems can be revealed by observational studies of their kinetic energy budgets. One approach that has received considerable attention is to represent the terms of the kinetic energy equation in wave number space and thereby partition the hemispheric kinetic energy budget into contributions made by different scales of motion. For convenience, the author will refer only to the review paper by Saltzman (1970), though it is recognized that this paper represents a compilation of results from a number of other researchers. Figure 1 presents Saltzman's winter (October–March) averages of kinetic energy, $K(n)$; conversion of potential to kinetic energy, $C(n)$; and nonlinear exchange, $N(n)$, as functions of planetary wave number (n). Considering the sources from which these statistics are derived, one would surmise that Saltzman's results are most representative of the Northern Hemisphere north of 15°–20° latitude and the layer extending from the surface to 100 mb, although some individual studies did extend beyond these limits. Figure 1 shows that, although the maximum kinetic energy resides in lower wave numbers, the intermediate wave numbers (e.g., $n=5$–10) exhibit the maximum conversion of potential to kinetic energy. Further, the kinetic energy produced at these scales is exported to other larger and smaller scale motions. Thus, these synoptic scales appear to be extremely important components of the general circulation of the middle latitudes.

As significant as this conclusion is, it still does not express fully the role of the synoptic scale in middle latitude circulations. Johnson (1970) has pointed out that a hemispheric diagnosis of eddy energy components may conceal more dramatic energy transformations occurring in individual systems of limited horizontal extent. Recent results of Petterssen and Smebye (1971) and Smith (1973) show that in the presence of an intense cyclone, synoptic scale systems can contain energy transformations that are significantly larger than corresponding hemispheric estimates.

This paper is intended to review the kinetic energy budgets of several examples of synoptic systems and to examine the contributions that these systems make to the general circulation of the middle latitudes. Included are supplementary analyses of the kinetic energy budget of a cyclone system previously reported by the author (Smith 1973) and an extension of this previous work to include the budget in the vicinity of an anticyclone, a class of pressure systems that has received very little attention in energetics studies.

2. CYCLONE SYSTEM BUDGET

For this study, the kinetic energy budget of a cyclone system is represented by a Eulerian budget calculated from data covering most of the North American Continent from the surface to 200 mb for the period 0000 GMT on Apr. 10 through 0000 GMT on Apr. 16, 1964. Further discussion of the data used in these calculations is given by Smith (1973). The synoptic situation is represented in figures 2 and 3, which contain respectively surface and 300-mb charts as derived from National Meteorological Center analyses at 1200 GMT on each day. Surface charts depict isobars of sea-level pressure in 4-mb increments and surface fronts. Upper air charts contain contours of height with increments of 120 m, heavy arrows indicating maximum wind axes and dotted curves representing isotachs in knots. Synoptic discussions are given in Chien and Smith (1973), Smith (1973), and previous work by

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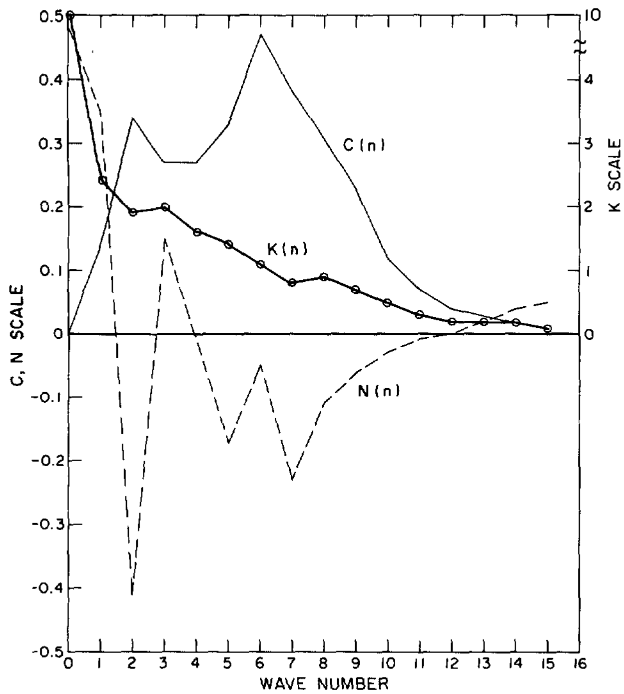

FIGURE 1.—Winter average kinetic energy, $K(n)$ ($10^5 \mathrm{J \cdot m^{-2}}$), conversion of potential to kinetic energy, $C(n)$ ($\mathrm{W \cdot m^{-2}}$), and nonlinear exchange $N(n)$ ($\mathrm{W \cdot m^{-2}}$) as a function of wave number (n). (From Saltzman 1970.)

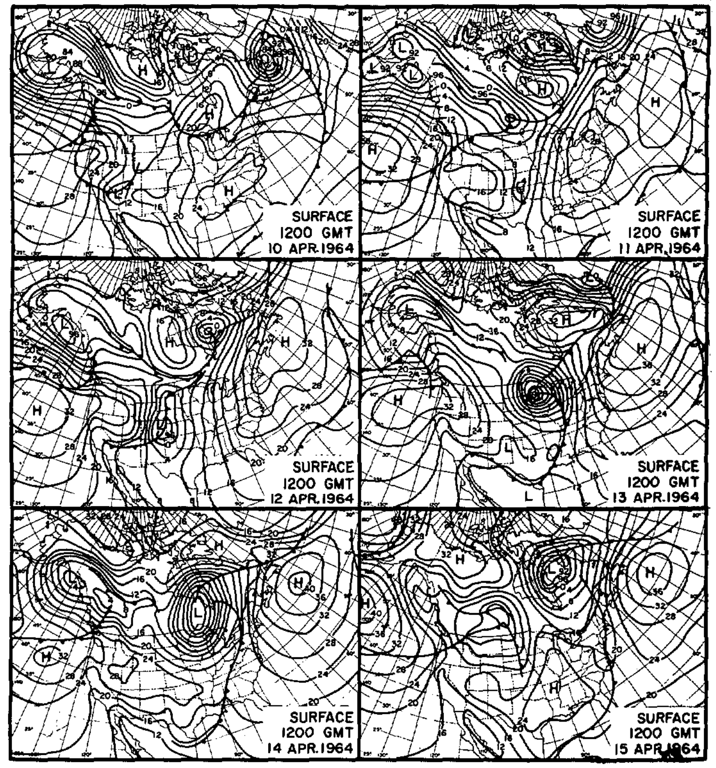

FIGURE 2.—Sea-level isobars (mb) and surface fronts for 1200 GMT, Apr. 10–15, 1964.

Krishnamurti (1968). Suffice it to say that the major feature is a cyclone that forms in eastern Colorado near 1200 GMT on April 12, intensifies to a central pressure of 972 mb by 1800 GMT on April 13, and finally occludes and fills as it moves northeastward across the north-central United States and Canada. Based on the surface charts and changes in central pressure, the period from 0000 GMT on April 10 to 1200 GMT on April 12 is referred to as the prestorm period; 1200 GMT on April 12 to 0000 GMT on April 14 as the growth period; and the remaining interval as the decay period.

The kinetic energy budget by period and by layer is summarized in table 1 and figure 4. Presented are calculations of terms in the Eulerian budget equation,

$$\underset{(a)}{\int \frac{\partial k}{\partial t}} = \underset{(b)}{\int -\nabla \cdot k\mathbf{V}} + \underset{(c)}{\int -\frac{\partial \omega k}{\partial p}} + \underset{(d)}{\int -\mathbf{V} \cdot \nabla \phi} + \underset{(e)}{D}, \qquad (1)$$

where

$$\int = \frac{1}{gA} \iiint dx\, dy\, dp,$$

A = area of the computational region,
∇ = horizontal del operator on a pressure surface,
$\mathbf{V}$ = horizontal wind vector with components (u,v),
ω = vertical motion in pressure coordinates (dp/dt),
$k = (u^2+v^2)/2$ = kinetic energy per unit mass,
$\phi = gz$,
$g = 980\ \mathrm{cm \cdot s^{-2}}$,
z = geopotential height of pressure surfaces,
p = pressure, and
x,y = west–east, south–north coordinates in a spherical, curvilinear coordinate system.

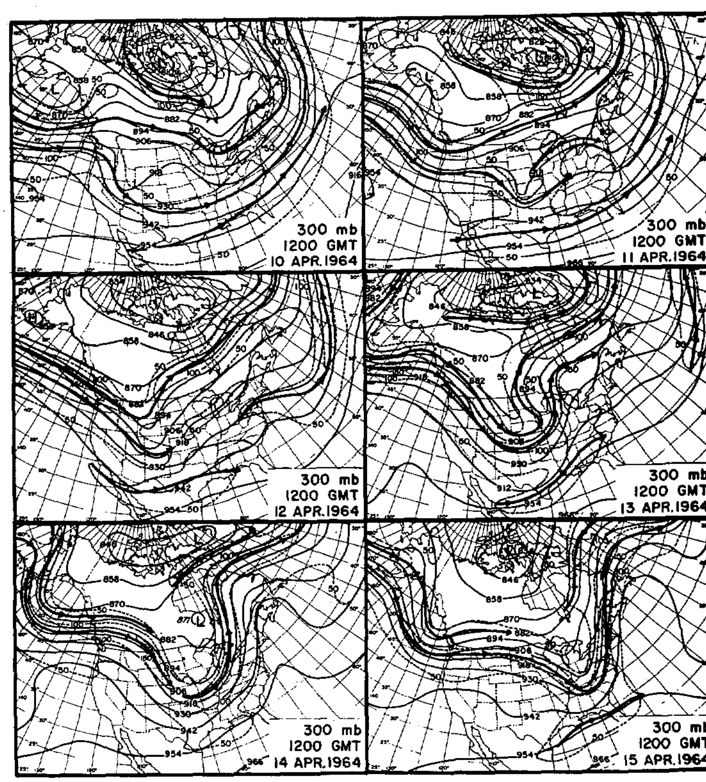

FIGURE 3.—The 300-mb height contours (dam, solid lines), maximum wind axes (heavy arrows). and isotachs (kt, dashed lines) for 1200 GMT, Apr. 10–15, 1964.

Equation (1) relates the time rate of change of kinetic energy, term (1a), to a set of energy sources or sinks. They are horizontal flux divergence, term (1b), vertical

TABLE 1.—*Cyclone system KE budget by periods. Units are $10^5 J \cdot m^{-2}$ for k and $W \cdot m^{-2}$ for energy changes*

Layer (mb)	k	$\frac{\partial k}{\partial t}$	$-\nabla \cdot k\mathbf{V}$	$-\frac{\partial \omega k}{\partial p}$	$-\mathbf{V} \cdot \nabla \phi$	D
			Prestorm			
400–200	7.9	−1.0	2.7	−0.2	3.1	−6.6
600–400	4.0	−0.4	0.0	0.4	−0.7	−0.1
800–600	1.8	0.0	−0.3	0.0	1.0	−0.7
sfc–800	0.8	0.3	−0.1	−0.2	2.4	−1.8
sfc–200	14.5	−1.1	2.3	0.0	5.8	−9.2
			Growth			
400–200	9.6	2.9	9.3	0.5	3.9	−10.8
600–400	5.6	2.5	1.8	0.5	1.2	−1.0
800–600	2.7	1.0	0.4	−0.5	1.3	−0.2
sfc–800	1.3	0.1	0.5	−0.5	3.6	−3.5
sfc–200	19.2	6.5	12.0	0.0	10.0	−15.5
			Decay			
400–200	9.9	−1.2	8.8	−1.5	−1.3	−7.2
600–400	5.6	−1.4	1.3	0.8	−1.0	−2.5
800–600	2.5	−0.7	−0.4	0.7	0.3	−1.3
sfc–800	1.0	−0.3	−0.2	0.0	2.3	−2.4
sfc–200	19.0	−3.6	9.5	0.0	0.3	−13.4
			Total			
400–200	9.0	−0.1	6.4	−0.4	2.2	−8.3
600–400	5.0	0.0	0.7	0.5	0.3	−1.5
800–600	2.3	0.0	−0.2	0.1	1.0	−0.9
sfc–800	1.1	0.0	0.0	−0.2	2.6	−2.4
sfc–200	17.4	−0.1	6.9	0.0	6.1	−13.1

flux divergence, term (1c), conversion of potential to kinetic energy, term (1d), and dissipation, term (1e). In general, terms (1a)–(1d) were computed directly from rawinsonde data subject to the boundary conditions $\omega=0$ at $p=200$ mb and $\omega=u=v=0$ at the surface, while the dissipation was estimated as the residual quantity required to balance eq (1). The del operation was performed in a spherical coordinate system with the inclusion of the converging meridian effect. Details regarding computing procedures are given in Smith (1973).

Table 1 reveals that each period is characterized by small changes in kinetic energy in the lower troposphere and somewhat larger changes in the upper trophosphere. The lowest layer reflects a near balance between gains attributed to conversion of potential to kinetic energy and losses attributed to dissipation. However, as one proceeds to higher layers, the transport (flux divergence) of kinetic energy becomes increasingly important because of strong jet stream intrusion (see fig. 3) through the western boundary of the computing region. Also coincident with this jet stream influence is the occurrence of a dissipation maximum in the 400- to 200-mb layer.

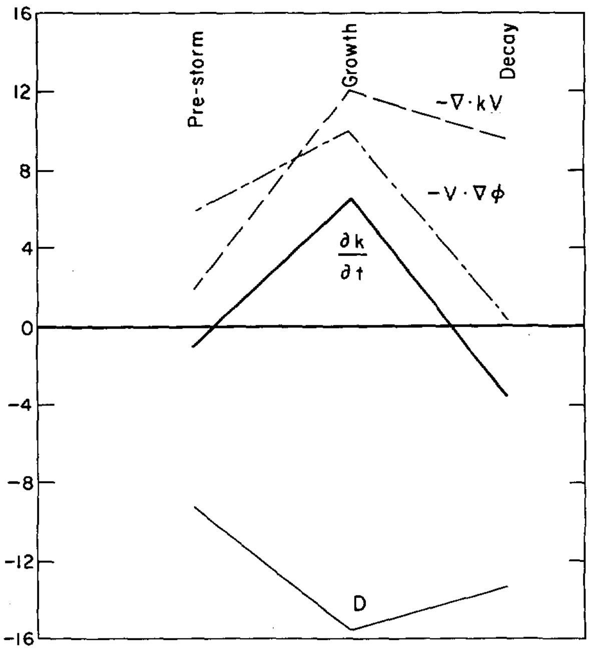

FIGURE 4.—Cyclone system kinetic energy budget ($W \cdot m^{-2}$) by period for surface to 200-mb layer.

During the prestorm period, the dissipation in the upper layer is sufficient to offset the sources provided by horizontal transport and conversion, and this accounts for the kinetic energy decrease. However, as the cyclone grows and the jet stream injection intensifies, energy conversion and transport combine to overwhelm the increased energy losses due to dissipation. Finally, as the cyclone decays, conversion of potential to kinetic energy occurs only in the lowest layers, and the dissipation process once again produces a depletion in the kinetic energy supply. Figure 4 is included to more effectively demonstrate the transition that the energy budget experiences as the cyclone system progresses through the three periods. All terms are minimum in the prestorm period, peak as the storm grows, and diminish once again as the system decays.

For purposes of comparison, the present results for the surface to 200-mb layer are included in table 2 with those of Petterssen and Smebye (1971) calculated for the surface to 100-mb layer for their first winter cyclone case. The latter paper was chosen because it describes a cyclone system of similar intensity to the present study (though occurring in a different season), spans the three periods described above, and is one of the most complete kinetic energy budget studies yet done. The present results are designated by S while those of Petterssen and Smebye are given as P&S.

As noted by Smith (1973), the two studies are consistent in their depiction of the rate of change of kinetic energy. Energy conversion and dissipation are of the same sign but differ in magnitude; the horizontal transports are of opposite sign. The sign of the transport differs because of the placement of the strong upper tropospheric flow with respect to the boundaries of the computing grid. As previously noted, the pesent study reflects strong jet stream

TABLE 2.—*Kinetic energy budgets by period for present study (S) and Petterssen amd Smebye (P&S). Units are the same as in table 1.*

Study	k	$\frac{\partial k}{\partial t}$	$-\nabla\cdot k\mathbf{V}$	$\frac{-\partial\omega k}{\partial p}$	$-\mathbf{V}\cdot\nabla\phi$	D
			Prestorm period			
S	14.5	−1.1	2.3	0.0	5.8	−9.2
P&S	27.8	−5.4	−13.1	−1.5	17.3	−8.1
			Growth period			
S	19.2	6.5	12.0	0.0	10.0	−15.5
P&S	27.0	2.8	−9.7	−1.0	19.8	−6.3
			Decay period			
S	19.0	−3.6	9.5	0.0	0.3	−13.4
P&S	26.3	−2.8	−9.4	−1.0	16.0	−8.4
			Total system			
S	17.4	−0.1	6.9	0.0	6.1	−13.1
P&S	27.0	−1.3	−10.6	−1.1	17.9	−7.5

intrusion, whereas the synoptic situation in P&S is characterized by upper tropospheric outflow. Differences in conversion and dissipation to some extent reflect computational uncertainties. However, physical explanations that are at least qualitatively plausible can be suggested. First, the intrustion of stronger winds into the wave system in the present study will tend to produce supergradient winds at a number of computational points. The resulting flow toward higher height values will partially offset the cross-contour flow toward lower heights normally expected in an intense cyclone system. On the other hand, if the strong winds are exciting the wave system, as in P&S, the flow toward lower heights will be enhanced and result in larger energy conversion. With regard to dissipation, P&S note the presence of relatively small vertical wind shears, while the author found a number of sizeable shears in his data. Hence, the dissipation values of S are larger than P&S.

For completeness and later reference, the author's previously documented results for the immediate vicinity of the cyclone are included in table 3. The storm vicinity includes the region enclosed by the last closed isobar of standard surface analyses at the middle observation time within each 12-hr period. The budget represents an average spanning the growth and early decay periods (1200 GMT on April 12–0000 GMT on April 15) with a total over all periods of 59 stations considered in the averaging process. More will be said of these results later; for the present, it will be sufficient to point out that the budget for the cyclone vicinity is qualitatively similar to that of the total cyclone system but differs quantitatively by a factor of about 3. Also, it is useful to note that the present energy conversion of 18.2 W·m^{-2} compares well with values of 16–21 W·m^{-2} calculated by Väisänen (1961), Palmén and Holopainen (1962), and Danard (1964), as summarized by Palmén and Newton (1969).

TABLE 3.—*Cyclone vicinity budget for the period 1200 GMT, April 12 to 0000 GMT, April 15, summarized with cyclone system budget. Units are the same as in table 1.*

Layer (mb)	$\frac{\partial k}{\partial t}$	$-\nabla\cdot k\mathbf{V}$	$-\frac{\partial\omega k}{\partial p}$	$-\mathbf{V}\cdot\nabla\phi$	D
400–200	−0.9	17.5	1.4	7.5	−27.3
600–400	1.9	4.9	−0.6	1.1	−3.5
800–600	2.1	0.7	−0.1	0.7	0.8
sfc–800	0.6	0.8	−0.7	8.9	−8.4
sfc–200	3.7	23.9	0.0	18.2	−38.4
Cyclone system sfc–200	−0.1	6.9	0.0	6.1	−13.1

Further, the surface- to 800-mb dissipation of −8.4 W·m^{-2} is comparable with the boundary-layer value of −7.5 W obtained by Bullock and Johnson (1971) for a storm of 1.1×10^3-km radius.

3. ANTICYCLONE VICINITY BUDGET

Since atmospheric motions respond to alternating periods of relatively higher and lower pressures, any attempt at detailed diagnostic analyses of large-scale eddies must include consideration of anticyclones. However, presumably because they are meteorologically less interesting, anticyclonic circulations have received little if any attention in energetics work. The following represents an analysis of a composit kinetic energy budget in the vicinity of the anticyclone dominating the eastern and southeastern United States from 0000 GMT on April 10 to 1200 GMT on April 11, the period preceding the major cyclone development discussed above. A total of 41 stations are considered in the tabulated averages. The upper air flow associated with the surface anticyclone is generally zonal with only weak perturbations appearing and although maxima are in evidence, 300-mb winds are less than 75 kt.

The budget results are presented in table 4 with the cyclone vicinity budget summarized for comparison. The characteristics of the two systems are obviously quite different. The anticyclone is a region of kinetic energy decrease induced primarily by horizontal outflow. The weaker wind fields and slower changes in height distributions with time result in substantially smaller energy conversions and dissipation. Clearly, this case represents an example of an energetically quiet circulation system.

4. KINETIC ENERGY ACTIVITY

Since one of the expressed purposes of this paper is to examine the role of individual synoptic scale systems in the general circulation of middle latitudes, it is important at this point to consider which terms of eq (1) represent reasonable comparative parameters. If comparisons were being made with the global general circulation as repre-

TABLE 4.—*Anticyclone vicinity budget for the period 0000 GMT, April 10 to 1200 GMT, April 11, summarized with cyclone vicinity budget. Units are the same as in table 1.*

Layer (mb)	$\frac{\partial k}{\partial t}$	$-\nabla \cdot k\mathbf{V}$	$\frac{-\partial \omega k}{\partial p}$	$-\mathbf{V}\cdot\nabla\phi$	D
400–200	−8.6	−7.2	−1.9	0.9	−0.4
600–400	−2.9	−4.4	1.1	−0.4	0.8
800–600	−1.1	−0.9	0.7	−0.6	−0.3
sfc–800	0.3	−0.2	0.1	0.5	−0.1
sfc–200	−12.3	−12.7	0.0	0.4	0.0
Cyclone vicinity sfc–200	3.7	23.9	0.0	18.2	−38.4

TABLE 5.—*KEA values ($W\cdot m^{-2}$) and contribution of synoptic systems to the middle latitude general circulation*

System	Fraction of middle latitude circulation	KEA	Fraction × KEA	Percent of general curculation
1. General circulation	1	11.1	11.1	100
2. Mean cyclone system	1/6	22.3	3.7	33
a. Prestorm	1/6	20.2	3.4	31
b. Growth	1/6	25.8	4.3	39
c. Decay	1/6	19.0	3.3	30
3. Cyclone vicinity	1/150	56.6	0.38	3
4. Anticyclone vicinity	1/150	0.4	.003	0.03

sented by multiyear means, then by necessity one would consider $\partial k/\partial t$, $-\nabla \cdot k\mathbf{V}$, and $-\partial \omega k/\partial p$ to be negligibly small compared to the conversion of potential to kinetic energy and dissipation. Thus, it seems appropriate to the author to consider the comparative energetic behavior of an individual system or region (e.g., middle latitudes) as being represented by these latter two terms; that is, the role of such a system will be given in terms of its internal transformations of energy.

A further consideration is required if one notes that the two internal terms tend to appear with opposite signs; therefore, a simple sum of the two will understate the energetic properties of a system. The author proposes to obviate this difficulty by defining a parameter called the kinetic energy activity (KEA) as the sum of the absolute values of the two terms,

$$\text{KEA}=|-\mathbf{V}\cdot\nabla\phi|+|D|. \qquad (2)$$

5. ROLE IN MIDLATITUDE GENERAL CIRCULATION

This section will examine the role of the systems discussed in the preceding sections in the general circulation of the middle latitudes. Since these discussions deal with specific case studies, the author does not intend that conclusions arrived at here should be interpreted as generalizations for all cyclone and anticyclone systems. On the contrary, it is likely that other cases would produce other results, and in view of the limited number of case studies reported in the literature to date, it would be improper to speak in broad generalities.

The comparative intensities of the various systems and the general circulation will be examined by considering the previously defined KEA as well as the conventional kinetic energy budget terms. For the general circulation, the author has chosen a KEA value of 11.1 $W\cdot^{-2}$ derived by averaging winter mean values of Kung (1969), Saltzman (1970), and Newton (1970). KEA and energy budget values for the mean cyclone system are given as the average of the present case study and that of Petterssen and Smebye (1971), as presented in table 2. Cyclone and anticyclone vicinity values correspond to estimates in tables 3 and 4.

Table 5 contains KEA values for each of these systems and their percentage contribution to the general circulation. Fractional values in column 2 are determined by estimating the relative area of each system compared to the area around the earth between 30° and 65°N. Column 4, the column 2 fraction multiplied by KEA, then represents an area weighting of the systems' KEA estimates. Finally, column 5 values are determined by dividing the results in column 4 for each system by the KEA value for the general circulation. The percentages indicate the relative contribution of each system to the general circulation.

Comparing KEA values in column 3, one sees that energy transformations occurring within the mean cyclone system considered here are about two times more intense than the general circulation, and further, within the immediate vicinity of a mature cyclone, the transformations approach levels five time larger than the general circulation. That the general circulation value is less is not surprising if one considers that this statistic includes the influence of many relatively dormant systems. The KEA results for the anticyclone vicinity suggest an example of a particularly quiet circulation feature.

Considering column 4 and the resulting percentages in column 5, one is presented with a different view of the energy transformations. Obviously, the total energy transformations in the middle latitudes are larger than any individual system because of the differences in areal coverage. Nevertheless, the percentage values provide further evidence that intense cyclone systems of the type reported here make substantial contributions to the general circulation. Indeed, these estimates suggest that as few as three intense cyclone systems could account for the great bulk of the energetic activity of the middle latitudes. If the KEA value for the general circulation is assumed to represent the polar cap in addition to the middle latitudes, then the energetic activity can be accounted for by four cyclone systems, similar to the conclusion drawn by Palmén and Newton (1969). On the other hand, the anticyclone case studied here contributes very little to the energy activity of the general circulation.

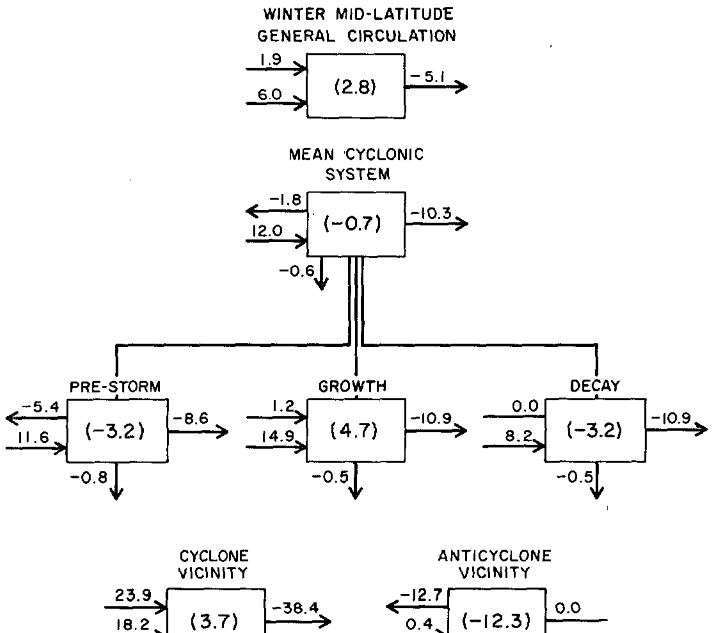

FIGURE 5.—Summary of kinetic energy budgets ($W \cdot m^{-2}$) for general circulation and various synoptic systems. The upper left arrow is horizontal transport, lower left is generation, right is dissipation, bottom is vertical transport, and the interior value is net time change. Arrows pointing outward (negative values) correspond to processes decreasing the kinetic energy.

It is also of some interest to examine the role of individual synoptic systems in the portion of the middle latitude circulations attributed to the intermediate scales. For this purpose, a KEA value for planetary wave numbers 6–10 has been derived by adjusting Saltzman's (1970) winter estimates upward in proportion to the total dissipation increase that resulted from averaging his value with that of Kung (1969) and Newton (1970). The resulting value for KEA (n=6–10) is 4.6-$W \cdot m^{-2}$. Thus, even though the mean cyclone system statistics contain contributions from other scales of motion, is it clear upon comparison with relative KEA estimates (column 4) in table 5 that such systems can exert a dominant influence on middle latitude synoptic scale energetics.

Finally, the energy budgets of the various systems discussed in this paper are summarized in figure 5. In addition to confirming the previously described importance of cyclone systems in the kinetic energy budget of the middle latitudes, it also calls attention to the significant influence of transport processes. In particular, the net energy changes computed for the prestorm period of the cyclone system, the cyclone vicinity, and the anticyclone vicinity are very much a response to the import or export of kinetic energy.

6. CONCLUDING REMARKS

The results of the preceding sections demonstrate that synoptic scale cyclone systems can be centers of intense energy exchange and that these systems can have profound influence on the general circulation of the middle latitudes. On the other hand, certain anticyclone systems represent very quiet components of the general circulation. As a final remark, the author would caution that too few case studies are available to suggest the "typical" roles of cyclone and anticyclone systems. To establish this, we must study many more cases. Also, it is well to recognize that a single mean value has been used for the KEA corresponding to the middle latitude general circulation. In reality, this value will undergo day-to-day variations. Hence, the relative contributions of individual systems will experience similar fluctuations.

ACKNOWLEDGMENTS

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